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(54) **Controlled flow rate capillary suction pump**

(57) A controlled flow rate capillary suction pump in which a liquid to be pumped is drawn by capillary action first through an open inlet tube in the form of a hole 4 formed in one of a pair of plates 1, 2 between which is sandwiched a sheet 3 of porous material. After leaving the hole 4, the liquid continues travelling through the porous material by capillary action and, in so doing, spreads out in all directions from the hole. Sensing means placed in hole 4 can be used to carry out tests on the liquid flowing at a controlled rate through the hole.

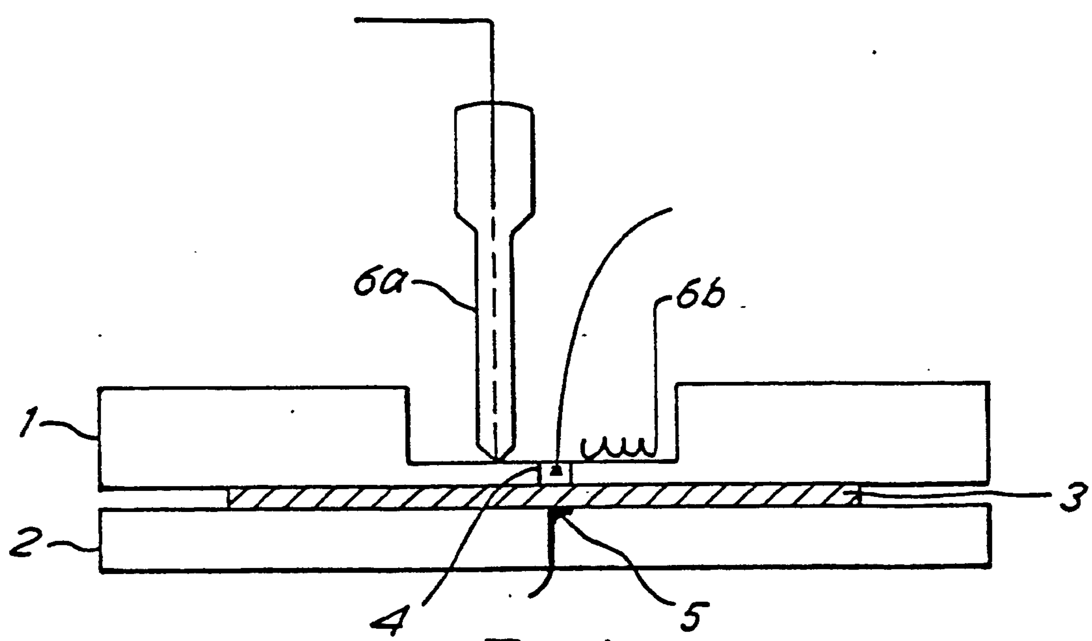

FIG.1

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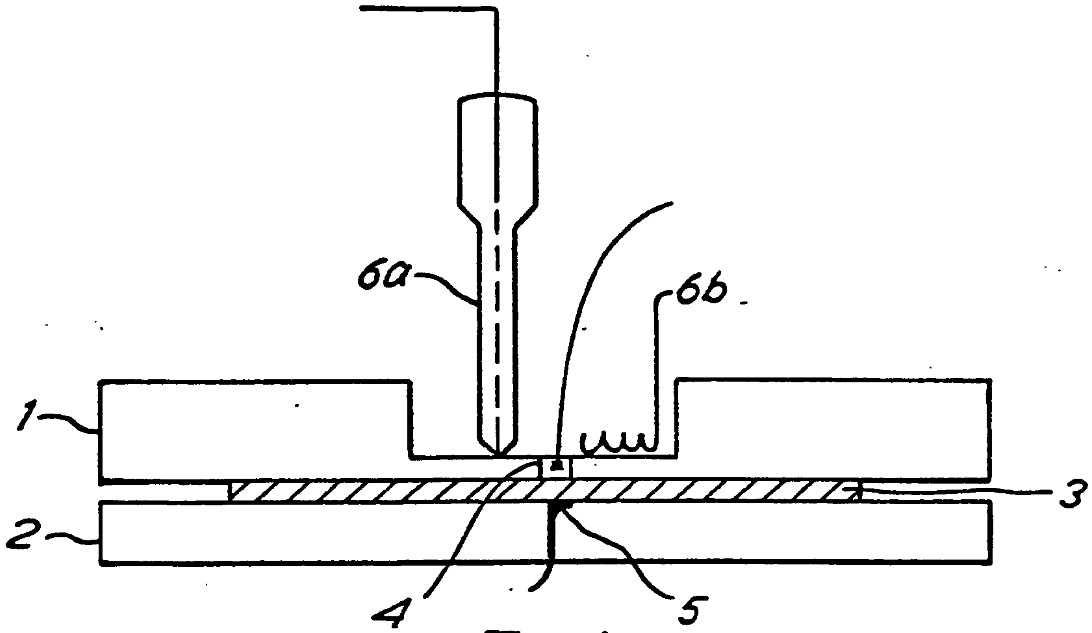
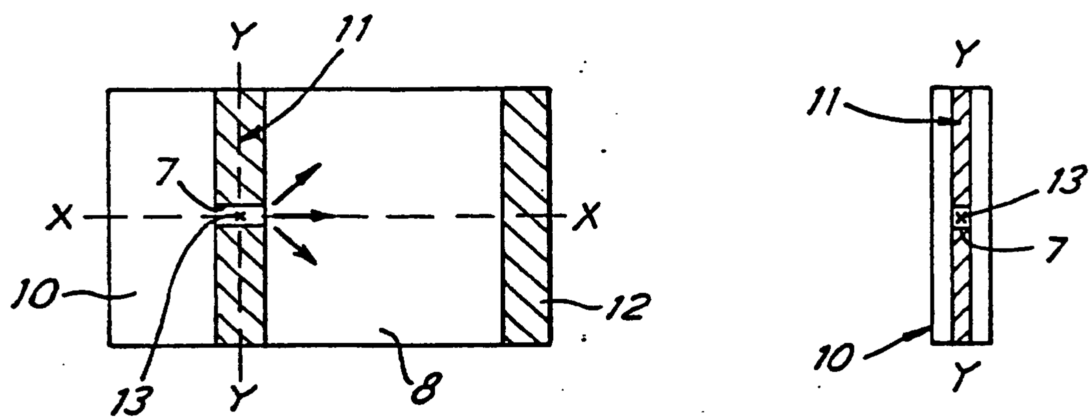


FIG.1



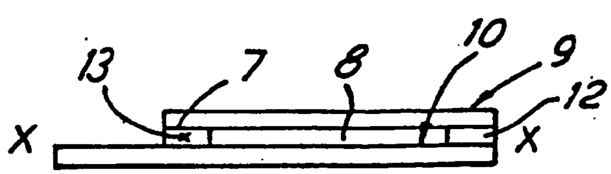


FIG. 3

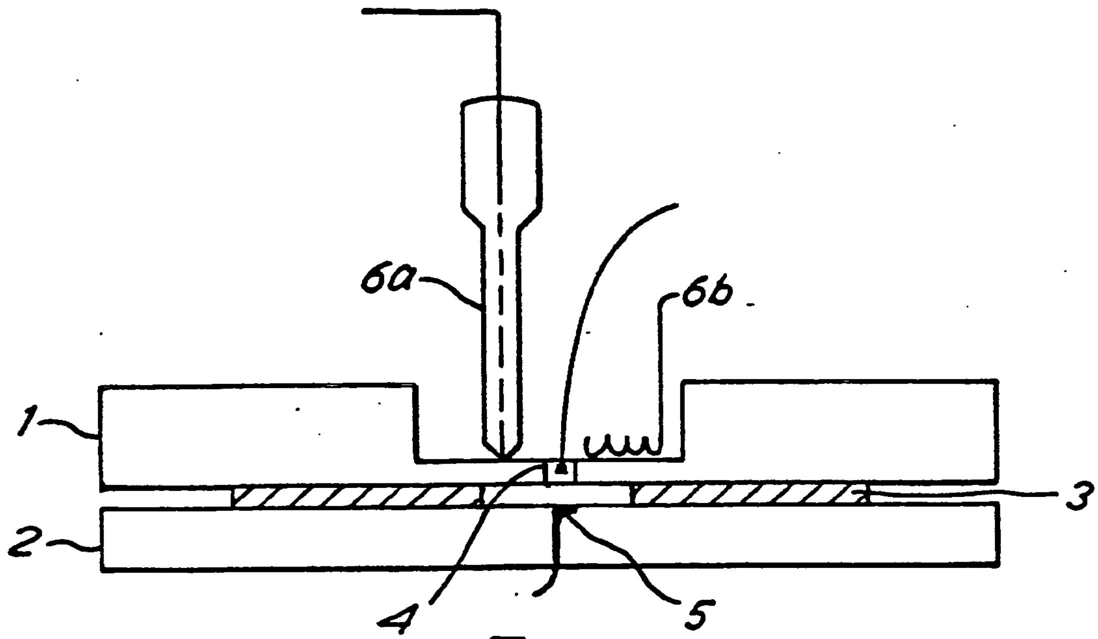


FIG. 2

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CONTROLLED FLOW RATE CAPILLARY SUCTION PUMP

This invention relates to a controlled flow rate capillary suction pump, particularly for use in chemical, biochemical and biological testing.

A small, fixed volume fluid sampling system, for use in chemical analysis has been described in International Patent Application No. WO86/00138. The system makes use of surface tension within a thin channel formed between two parallel plates to provide a self-filling sample chamber of well defined dimensions, and provides a simple and cheap mechanism for precisely defining the sample volume, thus permitting determination of the total amount of chemical species present and thus allowing its concentration to be evaluated.

In certain chemical analyses it is advantageous, instead of defining the volume presented to the sensing element, to define the volume flow rate past the element. Hydrodynamic voltammetry is such an analytical method, dependent upon a reaction rate measurement under conditions of defined flow rate, to determine concentration directly, Hydrodynamic methods would also be of use in direct immunochemical sensing at surfaces, allowing material from a comparatively large volume to be concentrated at a small sensing area, thereby enhancing sensitivity. The method would also facilitate the use of rate of change measurements and reduce measurement times for such immunoassay techniques. However, the method typically requires relatively elaborate equipment for defining solution flow, and calls for the use of relatively large sample volumes, thus reducing its gneral utility.

The inventor has appreciated, however, that surface tension and capillary rise phenomena can, if

proper account is taken of the factors controlling the rate of fluid intake, be employed to provide a simple, inexpensive suction pump with precisely defined flow rate, and the present invention provides such a pump.

In accordance with the invention there is provided a capillary suction pump comprising an open inlet channel having a size suitable to draw therealong by capillary action a liquid to be pumped, and a porous medium positioned in such a way as to receive the output of said inlet channel to thus maintain the liquid flow through said channel. In a chemical, biochemical or biological testing apparatus, one or more sensing elements are placed in the inlet channel and sample liquid is drawn past them at a defined flow rate set by the geometry and construction of the pump.

Preferably the inlet channel takes the form of a tube of a size suitable to cause the liquid to be drawn along it by capillary action. The input end of the channel may open into a small reservoir for holding the liquid to be pumped.

Preferably also the porous medium is positioned and arranged with respect to the output end of the inlet channel in such a way that, when a liquid being pumped leaves the inlet channel it is able to spread out in an arc of movement through the porous medium, thus providing a large number of passages through which the liquid can travel within the porous material by capillary action. Preferably this arc of movement is at least 180^{o}, and may be 360^{o}.

In an embodiment of the invention the process medium takes the form of a thin sheet of porous material sandwiched between two parallel plates. The inlet channel may take the form of a through aperture in one of said plates, or may be positioned in such a way as to bring the output end of the inlet channel

into communication with the edge of the porous sheet; for example the inlet aperture may be formed in spacer pieces used to space the parallel plates apart. In both cases, if the plates are close enough together to themselves exhibit capillary action in the absence of a porous filling, then the porous medium can be spaced back from the actual outlet end of the inlet channel so that liquid, after leaving the inlet channel continues to flow, by capillary action, between the plates until it reaches the porous medium. In this case the inlet channel is, in effect, extended between the parallel plates.

In a particular example of a pump in accordance with the invention, a porous medium (e.g. filter paper) is sandwiched between two parallel plates and a suitable inlet channel houses a sensing element capable of responding in a desired manner to fluid drawn past it at a defined flow rate set by the geometry and construction of the pump. Such an arrangement is compatible with disposable test strip methodology particularly prevalent in clinical chemistry.

In order that the invention may be clearly understood and readily carried into effect, the principles of operation thereof and some specific examples of the invention will now be described with reference to the accompanying drawings, of which:

Figure 1 shows, in schematic form a pump of impinging jet form; and

Figures 2 and 3 show, in similar form, alternative pump configurations.

For (laminar) flow through a porous medium it is necessary to consider two forces, first the surface tension force causing motion, which is proportional to the cross-sectional area perpendicular to the direction of flow, and second the viscous shear force opposing

motion which, from Newton's law of viscosity, is proportional to the fluid velocity and to the volume of fluid in motion. Hence, for a thin recatangular channel, thickness b, width w, filled to a distance x, for example, the application of simple Newtonian mechanics gives the expression:

$$FCM.bw - FOM.bwx.dx/dt = m.d^2x/dt^2 \qquad \text{Equation 1.}$$

where FCM and FOM are constants characteristic of the porous medium and fluid viscosity and m is the mass of the fluid. It is apparent that, as the channel fills, the viscous force, at a given velocity, will increase whilst the capillary suction force is constant such that the flow rate must decrease in order that the forces remain in balance. Neglecting the term on the right hand side (i.e. assuming viscous and capillary forces dominate over momentum) then the above equation can be solved and an expression for flow rate, Vf, as a function of time may be derived,

$$x = \sqrt{2FCM.t/FOM} \qquad \text{Equation 2.}$$

$$Vf = bw.dx/dt = bw\sqrt{FCM/2FOM.t} \qquad \text{Equation 3.}$$

This relationship has been verified experimentally using a rectangular strip of filter paper (Whatman 54) sandwiched betweent two equal sized glass plates (microscope slides), one edge of which is exposed to a solution reservoir.

The above result encourages consideration of the use of a radial flow geometry from a point source such that the capillary suction force increases with radial distance, and hence time, in order to counterbalance the effect of the increasing viscous shear force and so maintain constant flow rate. For

this geometry,

$$FCM.2\pi rb - \int_0^r FOM.2\pi rb.(dr/dt).dr = \int_0^r \rho 2\pi rb.(d^2 r/dt^2).dr \qquad \text{Equation 4.}$$

where ρ is the density of the fluid. Substituting (dr/dt = Vf/2πrb and integrating first with respect to r and then with respect to t with initial condition Vf - 0 at t = 0 gives:

$$Vf = (FCM.2\pi b/FOM).(1-\exp(-FOM.t/\rho)) \qquad \text{Equation 5.}$$

Hence, after an initial start up time, the exponential term becomes insignificant and a constant flow rate is established. The validity of this expression has been established using the same arrangement as described earlier but with a thin wick at a corner of the rectangular channel providing a point source of fluid from the reservoir and from which fluid spreads out radially. It is evident from the above expression for volume flow rate that, according to the application, the required rate may be achieved by choice of the porous medium which determines the characteristic constant FCM and FOM or by choice of its thickness, b.

The system has also been tested using an impinging-jet electrode configuration to prove its applicability to mass transport rate (current) measurement and hence voltammetric determination of concentration. The system employed is shown in Figure 1, and comprises two plates 1 and 2, between which is sandwiched a 40mm diameter disc 3 of filter paper 200μm thick. The upper plate 1 has a central inlet hole 4 of 1mm diameter, directly above a correspondingly dimensioned sensing gold disc electrode 5 set in the bottom plate 2. A small drop of sample fluid applied

above the inlet hole 4 is drawn into the porous layer 3. Reference and counter electrodes 6a, 6b positioned adajcent to the inlet hole 4 make contact with the solution, allowing conventional potentiostatic control and hence voltammetric analysis of the system. Flow rate measurements (r^2 vs time) for this system show a minor deviation from linearity which may be ascribed to the influence of an additional, constant gravity (hydrostatic pressure) force which becomes less significant compared with the capillary suction and viscous forces at longer times such that the flow rate then becomes steady. This effect may be allowed for automatically, since it is known and predictable, if desired, or it may be eliminated by appropriate modification of geometry. Stationary and hydrodynamic voltammograms for potassium ferricyanide (2mM) have been obtained using the system and demonstrates its effective electrochemical operation. Monitoring of current vs time demonstrated that, after an initial start up transient, presumably due to both hydrodynamic and electrochemical transient phenomena, a steady current is obtained, which later decays as the filter paper disc fills and the fluid flow ceases.

In the alternative arrangement, shown in Figure 2, the central portion of the disc 3 is cut out in registry with the inlet hole 4, so that the disc 3 becomes of annular shape. Sample fluid, upon leaving the hole 4 spreads out in all directions towards the disc 3. The fluid continues to travel, until it reaches the disc, by capillary action between plates 1 and 2.

The applicability of the capillary suction pump system to quantitative chemcial analysis is established by current measurement over a range of concentrations of electroactive species. Results demonstrate that

current, i, measured after the flow rate has stabilised at around 100 seconds, is directly proportional to concentration, C, in accordance with the relationship

$$i = k_D F C \qquad \text{Equation 6.}$$

where F is Faraday's constant and k_D is the flow rate dependent mass transport rate constant.

As well as providing stable and defined flow conditions, a suitably impregnated porous medium can provide sample pretreatment or reagant addition if required.

Figure 3 shows a schematic configuration of an alternative form of the invention to the so-called impinging jet system shown in Figure 1. In the arrangement of Figure 3, a rectangular inlet channel 7 is formed in the same plane as the porous capillary suction medium 8, rather than perpendicular thereto, as in the systems of Figures 1 and 2.

In the arrangement of Figure 3, the medium 8 is sandwiched between flat top and bottom plates 9, 10 respectively, and barriers of epoxy material 11, 12, are provided between the plates at the inlet and opposite ends respectively. A sensor, shown schematically at 13, is disposed in the inlet channel.

The shaping of the path to be followed by the fluid is critical in determining the flow-rate characteristic of the pump and though the primary aim of the invention currently is the provision of a constant defined flow rate, the capillary suction pump can equally well be employed to provide defined increasing or decreasing volume flow rates, according to its geometry.

CLAIMS

1. A capillary suction pump comprising an open inlet channel having a size suitable to draw therealong by capillary action a liquid to be pumped, and a porous medium positioned in such a way as to receive the output of said inlet channel to thus maintain the liquid flow through said channel.

2. A pump as claimed in Claim 1 wherein said inlet channel is a tube.

3. A pump as claimed in either one of Claims 1 and 2 wherein the porous medium is positioned and arranged with respect to the output end of said inlet channel in such a way that, when a liquid being pumped leaves the inlet channel it is able to spread out in an arc of movement through the porous medium.

4. A pump as claimed in Claim 3 wherein the included angle of said arc of movement is at least 180°.

5. A pump as claimed in Claim 4 wherein the included angle is 360°.

6. A pump as claimed in any one of the preceding claims wherein the porous medium takes the form of a thin sheet of porous material.

7. A pump as claimed in Claim 6 wherein said sheet of porous material is sandwiched between two parallel plates.

8. A pump as claied in Claim 7 wherein said inlet channel takes the form of a through hole in one of said plates.

9. A pump as claimed in Claim 8 wherein said hole is positioned in such a way that it opens into a central area of said porous sheet, thus causing liquid being pumped to spread through a 360° arc upon leaving the hole.

10. A pump as claimed in Claim 8 wherein the sheet

of porous material is formed with an aperture in line with said hole, said aperture being larger in size than said hole whereby liquid, upon leaving the hole, continues to flow towards the porous material by capillary action between the plates.

11. A pump as claimed in Claim 7 wherein said inlet channel takes the form of a through hole formed in a spacer member provided between the plates so that the liquid being pumped is directed towards the edge of the sheet of porous material.

12. A sensor incorporating a pump as claimed in any one of the preceding claims and further incorporating one or more sensing elements positioned within said inlet channel.

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